KOEP: Annual Technical Progress Report

Cover page

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Institution:	**University of Kentucky**	
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Clean Coal Processes:
Vortecone® Modification for Emission Control at Coal-Fired Power Plants

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Abstract

In the first year of this 2 year project, we have conducted experimental tests to analyze fly ash samples, collected from Paradise and Shawnee power plats both located in Kentucky, for loss of ignition (LOI), size distribution and SEM imaging of shapes of ash particles, unburned carbon contents, and hollow spheres. The reference cyclone was determined for dimensions and inlet parameters, prepared for numerical simulation tests. Current Vortecone® computer code, which was successfully applied to the Toyota paint booths and reduced a large amount of energy costs, was modified for applying in capturing coal-combustion fly ash at power plants, and Vortecone® performance was compared with the reference cyclone. The preliminary study shows that with a slight modification, Vortecone® technology can be applied in capturing coal-combustion fly ash at power plants. As compared with the reference cyclone during the performance of fly ash capturing, the pressure drop in Vortecone®was 30-37 % less, implying that, at least, 30% of energy can be saved for power plants in capturing fly ash. Vortecone® was estimated to be 7.6-12.6 times less polluting than standard cyclones, because it can capture smaller fly ash particles than cyclones, which benefits to the environment.

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Vortecone® Modification for Emission Control at Coal-Fired Power Plants

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1. Introduction

There are more than 720 coal-fired power plants in the U.S. which produced 76 million tones of fly ash per year. The EPA is currently mandating reduction of particulate emissions by coal-fired power plants with a new focus on small particles less 2.5 μm ($PM_{2.5}$). There is no current technology available particularly developed for effectively capturing these $PM_{2.5}$ and bonded mercury emissions from coal-fired power plants. These issues affect both Kentucky's coal industry as well as Kentucky power plants that use coal as fuels. New green technology to recover small particulate and to remediate particulate escaped at transfer points would help make the continuous use of coal in power plants a viable option both economically and environmentally, as called for in Kentucky's *Comprehensive Energy Strategy*, as developed by the Governor's Energy Policy Task Force, embody Governor Fletcher's guiding principles for Kentucky's energy future.

1.1 <u>Review of current emission control techniques</u>

a. <u>Greenhouse gas emission reduction</u>
Greenhouse gas is the carbon dioxide (CO_2) released into atmosphere from fuel combustion. Also CO_2 concentration in air is less than 0.04 %, it has increased 25 % in the last century and may doubled by the end of the next. The CO_2 in air can absorb heat that would ordinarily radiate into space from earth surface, resulting in global warming. There are technologies available to capture CO_2 from power plant emissions, while the cost is extremely high. Use reproducible energies such as wind, solar, hydro energy and the energies from agricultural products can reduce greenhouse gas emissions. Minimizing use of energy and natural resources is the economical way to reduce greenhouse gas.

b. <u>Sulfur dioxide (SOx) and Nitrogen oxides (NOx) emission reduction</u>
SOx and NOx are pollutant gases, former can create acid rain that harms environment and human activity, while later harms human's respiration system. They are mainly from burning fossil fuels and motor-vehicle exhausts. NOx formation can be controlled by using low NOx burners. Selective catalytic reduction (SCR) and non-selective catalytic reduction (NSCR) are approved to be appropriate devices for power plants and other industries to control NOx formation as well as to capture mercury in the flue gas line. Fluidized-bed technology with flue gas recirculation can control both SOx and NOx formations. In the fluidized bed, the fuel and limestone are charged to the combustion devices and fuel-sulfur reacts with limestone to produce solid calcium sulfate. Recirculation of flue gases and limestone particles can increase the consumption rate of limestone and reduce the peak flame temperature, leading to a reduced NOx formation.

c. <u>Mercury and other toxic compounds</u>
There are a number of technologies available to control mercury and other toxic compounds emission released from coal burning. For example, the devices that are used to control SOx, NOx and particulate can also remove mercury by injecting activated carbons into the flue gas line. The effectiveness of these technologies from mercury removal varies, depending on characteristics of coal fired in the boilers and

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the configuration of power plants. Because mercury usually bounded on carbon particles, it is possible to remove mercury together with capturing particulate matter. Therefore, the modified Vortecone® technology may also be able to remove mercury.

d. Particular matter

Conventional devices such as cyclones and electrical precipitators can capture fly ash particles larger than 10 μm in diameter (PM_{10}). There is no exiting technology available to efficiently capture PM_{10} or less. Fortunately, our Vortecone® technology developed by UK and Toyota was verified in the Toyota paint booth that is able to efficiently capture the paint droplets less than 10 μm. Additional advantage of using Vortecone® in paint booth is the significant energy saving. Therefore, the modified Vortecone® technology may be able to capture fine particulate as well as mercury at coal-fired power plants.

1.2 Background of Vortecone® technology

The Vortecone® technology was jointly invented by Dr. Kozo Saito's research team in UK and Toyota engineers that captures small (sub-micro) particles of over-sprayed paints using special vortex chambers. Toyota in-plant tests proved that the Vortecone® technology is highly effective both in capturing paint particles and reducing energy costs. This patented device is fully developed and commercialized, currently installed in seven Toyota assembly plants both in U.S and Japan. The inventors are confident that the Vortecone® can be adapted after modification to effectively and economically capture small airborne particulate such as fly ash and sub-micron particulate matter.

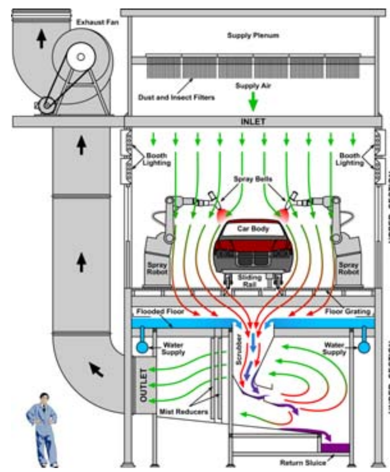

Figure 1. Schematic of paint booth

1.3 Success of Vortecone® applied to Toyota plant booths

Toyota has invested in the project to develop Vortecone® for three years and investment was more than \$1,070,000. It was installed in seven Toyota assembly plants to capture over-spayed paints. The daily operations in these 7 plants show that Vortecone® has a high volumetric capturing efficiency (> 99.5%) and lower pressure drops, and is capable to capture smaller paint particles as compared with current scrubbers previously installed in the plants, resulting in substantial energy savings during booth operation. Figure 2 compares the pressure drop and mass penetration of the particles between Vortecone® and conventional scrubbers. The penetration is a more appropriate index than efficiency because it shows the amount of particulate matter mass released. The results show that Vortecone® has much less penetration than scrubbers. More importance shown in Fig. 2 is the pressure drops. Less pressure drop means energy savings. Currently, 7 Toyota plants have installed Vortecone® system. It was estimated that in 2005, Toyota Indiana plant along has saved \$337,000 dollars for energy cost because of less pressure drop in paint booth with Vortecone®. Considering less maintenance and cleaning costs, the total savings were \$4.4 millions for paint-related costs. In all 7 Toyota plants installed Vortecone®, it was estimated that \$6.34 million

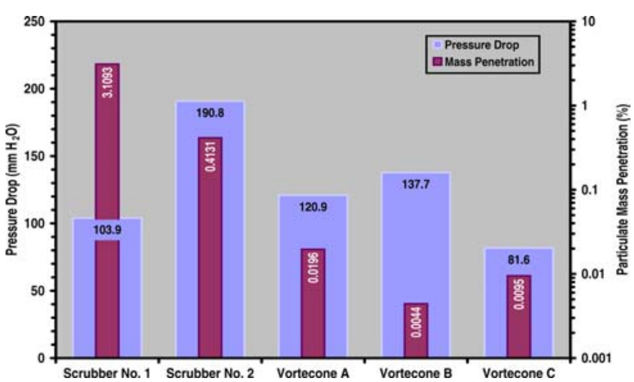

Figure 2. Comparison of Vortecone® performance with conventional scrubber as plotted the pressure drop and mass penetration of paint particles.

dollars was saved for energy costs each year due to application of Vortecone® technology.

The Commonwealth of Kentucky has invested $300,000 indirectly in the Vortecone® project via the Painting Consortium portion by KEDFA award to the Visualization and Virtual Environment Center, about 22% of the total project award. The public benefits due to invention of Vortecone® include 8 new jobs at Trinity to build Vortecone®, 4 jobs for retaining, and 8 manufacturing jobs. If including the tax revenues (unknown), the total ration of public output to the investment is around 425 %.

2. Objectives and Technical Tasks

Overall objectives of the project is to conduct a serious of feasibility studies to evaluate the application of already proved Vortecone® technology to capture fly ash, small particulate, and possibly the mercury emission from coal-fired power plants. The project includes four technical tasks. The details of tasks and progress of the project are shown in Table 1. According to the proposed project schedule, progress was achieved on time (red symbols). There is no delay of the project tasks (blacks symbols are the future tasks).

Table 1. Project Tasks and Timetable

Tasks	**Quarter**							
	1	2	3	4	5	6	7	8
Task 1. Site visit and data collection (4 months)	✏	✏						
Task 2. Analysis of plant site data (2 months)		✏						
Task 3a. Modification of computer code (8 months)			✏	✏				
Task 3b. Conduct simulation				✏	✏			
Task 4. Lab model experiments						✏	✏	✏
Task 5. Summarize the findings					✏			✏
Reports	✏	✏	✏	✏	✏	✏	✏	✏

3. Progress of the Project

3.1 Fly ash analysis

Three fly ash samples were collected from two power plants during our visits. In Paradise Fossil Plant in Drakesboro, KY, electrostatic precipitators were installed to capture fly ash, while in Shawnee Fossil Plant in Paducah, KY, cyclones were used for fly ash capturing.

a. Appearance of fly ash

Figure 3 is the SEM images of fly ash and carbon burnt-out ash samples. The spheres shown in Fig. 1 (left) are ash particles (SiO_2) having different diameters. The irregular shapes are unburned carbons. Because of installation of low NOx burners in the power plants, the lower flame temperature, which can reduce NOx formation, was traded with high unburned carbon content in fly ash. The carbon content or Loss of Ignition (LOI) of Shawnee #2 fly ash sample was experimentally measured to be 9.21%, greater than standard value of LOI (3%), below which fly ash can be used for cement production.

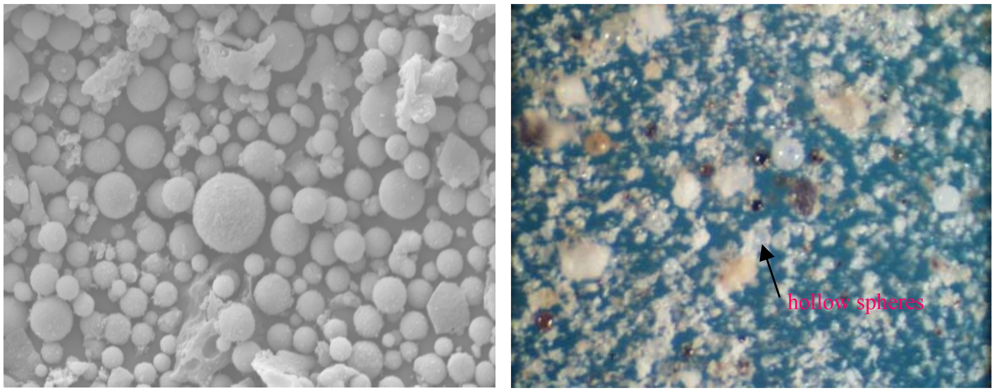

Figure 3. SEM images of coal-combustion fly ash (left), showing spherical ash particles and irregular unburned carbons. Image of carbon-burned out ash, (right) showing hollow spheres, the value-added materials.

The right image in Fig. 3 is the fly ash sample after carbon burned out. It displays hollow spheres, the value-added materials due to light. They are excellent thermal-resistant materials.

b. Size distribution of fly ash

Size distribution is important parameter both for the numerical simulation and experiments. Figure 4 is the measured size distribution and the cumulative value for the Shawnee #2 ash samples (Results of other two samples are similar). Majority of particles are between 1 to 20 μm. Cumulative plot provides a statistical variation of the particles, that is, the diameter of particles at 10% population density is less than 1.15 μm, at 50 % less than 7.74 μm, and at 90 % less than 20.4 μm. The mean diameter of this ash sample is 9.62 μm.

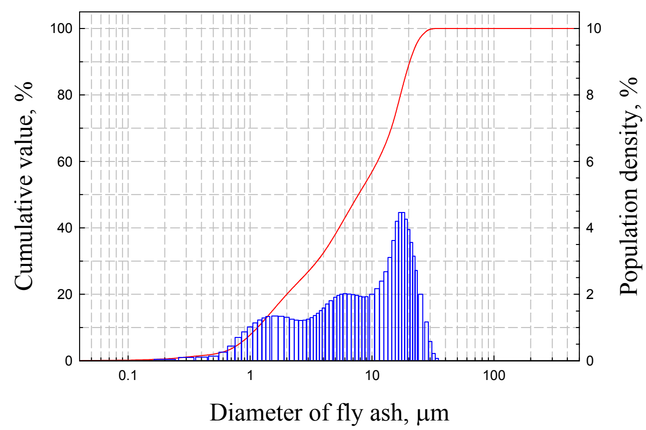

Figure 4. Size distribution and cumulative value for the Shawnee fly ash sample #2.

3.2 Evaluation of cyclone performance

a. Determination of inlet parameters and operational conditions

In order to compare Vortecone® performance with the reference cyclones, it requires cyclone parameters, including dimensions, inlet and outlet parameters (see Fig. 5). We estimated the cyclone parameters by first determining the basic dimensions of conventional large cyclones, based on the flow rate of Shawnee cyclones (10,156 acfm) and using parameter dependence shown in Table 2. Design of a standard cyclone uses dimension relations shown in Table 3.

Table 2.Cyclone parameter dependence

Air flow rate (acfm)	Inlet velocity (fpm)	Pressure drop (inch w)
5000-8000	4670-6465	16.1-7.1
8000-11500	4530-6510	15.1-5.5
8000-13000	4530-7360	18.8-7.0

Table 3. Standard cyclone dimensions

Body diameter	$D/D = 1.0$
Height of inlet	$H/D = 0.5$
Width of inlet	$W/D = 0.25$
Diameter of gas exit	$D_e/D = 0.5$
Length of Vortex finder	$S/D = 0.625$
Length of body	$L_b/D = 2.0$
Length of cone	$L_c/D = 2.0$
Diameter of dust outlet	$D_d/D = 0.25$

b. Parameter estimation

For our reference cyclone, the flow rate is 10,156 acfm, the corresponding inlet velocity is between

4530 and 7360 fpm, and the pressure drop between 18.8 and 7.0 inch water, as shown in Table 2. The inlet parameters of the cyclone can be estimated by use of a very simple model with the equations show below.

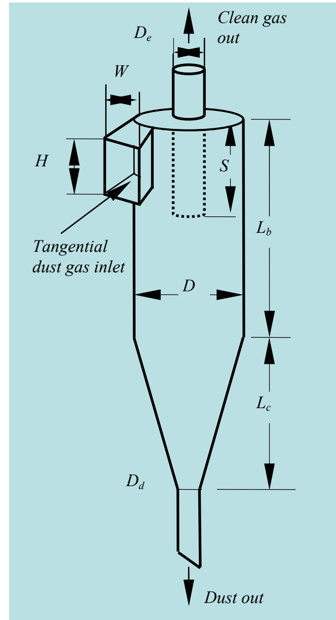

Figure 5. Cyclone dimensions

Inlet velocity

$$V_{in} = Q / WH \tag{1}$$

Gas revolution is the cyclone

$$N_e = \frac{1}{H}(L_b + \frac{L_c}{2}) \tag{2}$$

Gas resident time in the cyclone

$$\Delta t = \pi D M N_e / V_{in} \tag{3}$$

50% cut diameter of the particles

$$d_{pc} = \left[\frac{9\mu W}{2\pi N_e V_{in}(\rho_p - \rho_g)} \right]^{1/2} \tag{4}$$

Particle terminal velocity

$$V_{ex} = \frac{(\rho_p - \rho_g) d_{pc}^2 V_{in}^2}{9\mu D} \tag{5}$$

Efficiency of particles in jth size range and overall efficiency

$$\eta_j = \frac{1}{1 + (d_{pc} / d_j)^{1/2}}, \qquad \eta = \frac{\sum \eta_j m_j}{m} \tag{6}$$

Using this simple cyclone model, the inlet velocity is 21.3 m/sec, gas resident time in the cyclone 1.22 sec, the diameter of particles at 50% cut volume 6.9 µm, the particle terminal velocity 0.123 m/sec, and overall efficiency in the reference cyclone for the Shawnee fly ash is 88.25%. These parameters are used in the numerical simulation for both cyclone and Vortecone®.

3.3 Modification of Vortecone® computer code

Modification of the current UK Vortecone® computer code for capturing over-sprayed paint particles was conducted to satisfy the changes for capturing fly ash. For comparison, the reference cyclone also needs simulation. The CFD geometry and mesh for this cyclone is shown in Fig. 6 (left). The calculation uses

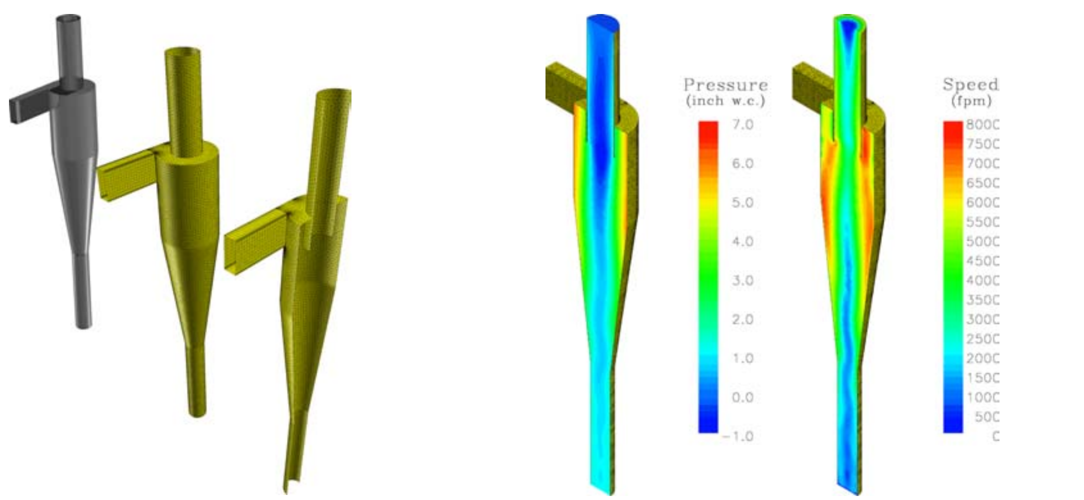

Figure 6. The reference cyclone, (left) CFD geometry and mash, (right) calculated pressure drop and speed.

hybrid grid with complex geometries. With Lagangian-Eulerian simulation approach, the k-ω turbulence model was applied together with 2nd order upwind to treat convective terms. The multi-grid solution strategy and scrubbing water modeling are also used in the Vortecone® simulation. All equipment tested is handling 10,156 acfm flow rate. Figure 6 (right) is the results of calculated pressure drop and speed for the reference cyclone and these for original Vortecone® design are shown in Fig. 7.

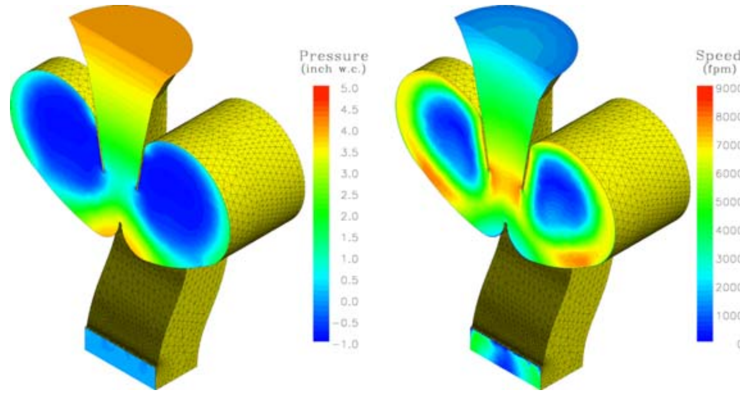

Figure 7. Calculated pressure drop and speed for original Vortecone@ configuration.

Simulation was also conducted for Vortecone® No. 1 (Fig, 8, top) and No. 2 (Fig. 8, bottom). The comparison between cyclone and three Vortecone® configurations is shown in Table 4. This table presents an estimation of pressure drop (ΔP), based on our CFD results. Pressure drop relates directly to the operational cost of the device because power needed for operation is directly proportional to the flow rate and pressure drop. Completed simulation tests verified that Vortecone® A is 30% more energy efficient than the reference cyclone. A slightly modified Vortecone® A can be 37 % more energy efficient. The value of penetration for the Vortecone® A configurations were found to be between 7.6 – 12.6 times lower than that estimated for the cyclone.

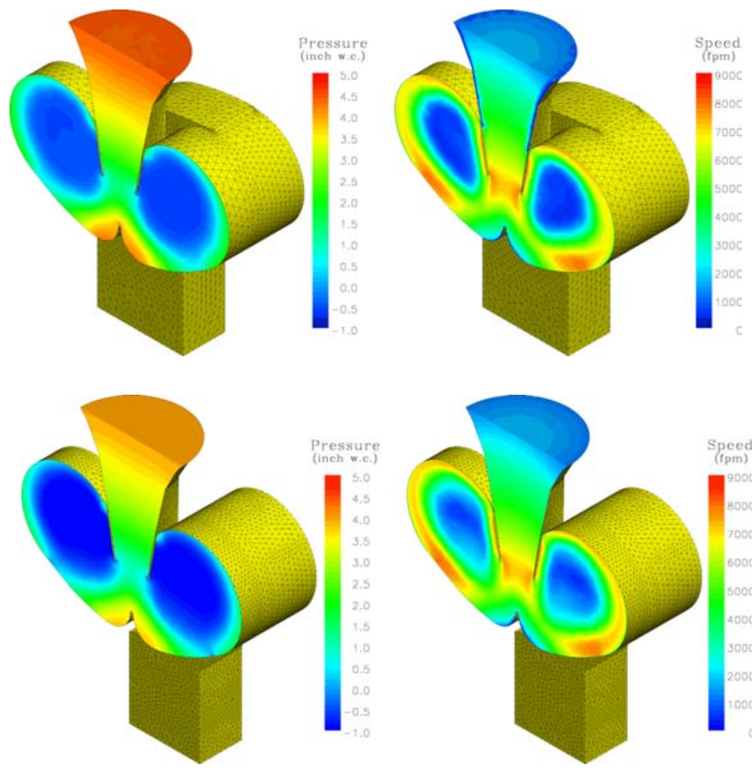

Figure 8. Calculated pressure drop and speed for Vortecone@ #1 (top) and Vortecone@ #2 (bottom).

Table 4. Comparison of Vortecone®pressure drop with reference cyclone.

Device	**Cyclone (installed)**	**Vortecone® A (original)**	**Vortecone® A (mod. No. 1)**	**Vortecone® A (mod. No. 2)**
ΔP (inch w.c.)	6.395* (baseline)	4.468 (30.12% ↓)	4.077 (36.25% ↓)	3.999 (37.47% ↓)
Penetration (%)	11.75 (baseline)	1.55 (7.6 times ↓)	1.90 (6.2 times ↓)	0.93 (12.6 times ↓)
η = Efficiency (%)	88.25	98.45	98.10	99.07

Summary

In the first year period of this 2 year project, we have conducted experimental tests to analyze collected fly ash for LOI, size distribution, and SEM imaging for ash particles, unburned carbon and hollow spheres. The reference cyclone was determined for dimensions and inlet parameters, prepared for numerical simulation tests. Modification of current Vortecone® computer code was completed for comparison of Vortecone® performance with the reference cyclone. The preliminary study shows that with modification, Vortecone® technology can be applied in capturing coal-combustion fly ash from power plants. As compared with the reference cyclone in fly ash capturing, the pressure drop in Vortecone® was 30-37 % less, implying that, at least, 30% of energy can be saved with application of Vortecone® in power plants in the processes of fly ash capturing. Vortecone® was estimated to be 7.6-12.6 times less polluting than standard cyclones currently in use at Shawnee plant, and can capture smaller fly ash particles than cyclones, which benefits to the environment.

Tasks for Year 2 (7/1/07-6/30/08)

1. Modification and upgrade of current Vortecone® computer program code to apply for capturing coal-combustion fly ash.
2. Conduct numerical simulations for simple and small laboratory scale capturing cases
3. Conduct experiments to validate Vortecone® computer code in capturing fly ash, possibly mercury as well, at a full scale by developing scaling laws

References

1. Russel W. Bessette, Measuring the economic impact of university-based research, *J. of Technology Transfer*, 28:355-361, 2003. [NY state office of science, technology and academic research].
2. A.N. Link, A suggested method for assessing the economic impacts of university R&D: including identifying roles for technology transfer officers, *J. of the Association of University Technology Managers*, XI, 1-17, 1999.
3. C.D. Cooper and F.C. Alley, Cyclones, Adapted from Air Pollution Control, 1986.

Supplemental Information

A. **Status of project personnel (hired, started, continuing, etc).**
Please include: First, last name, academic level, gender, ethnicity, department, university/organization affiliation, and status for each person.
- Dr. Kozo Saito (PI), Professor, Male, Dept. of ME, UK, supervise the project
- Dr. Abraham Salazar, (Co-PI), Assistant Professor/Res, Male, Dept. of ME, UK, modeling and numerical simulation
- Dr. Tianxiang Li (Co-PI), Assistant Professor/Res., Male, Dept. of ME, UK, experiments
- One graduate student will join the team.

B. **Grant and contract proposals submitted.**
Please include: *Agency, PI, Co-PI, project title, $ requested, date submitted for each proposal.*
- N/A

C. **Grant and contract awards received .**
Please include: *Agency, PI, Co-PI, project title, $ awarded, date received, start date of grant and length of grant for each grant.*
- None

D. **Manuscripts submitted/published.**
Please include: *Journal, article title, authors, and status or date accepted, & journal reference for each.*
- No manuscripts related to this project are submitted/published.

E. **Invention disclosures, filing of patent applications, and technology transferred.**
Please include: *Application type, title, inventors, date applied, assigned number, and status of each application, and details of technology transferred, if any.*
- None

F. **New collaborations.**
Please include: *First/Last name, university/organization affiliation, department, gender, ethnicity, collaboration type (i.e. university/industry), and nature of collaboration for each.*
- Paradise fossil plant, TVA, Drekesboro, KY
- Shawnee fossil plant, TVA, Paducah, KY

G. **Presentations.**
Please include: *Conference title or location description, city, state, date, presentation title, type, and presenters for each.*
- None

H. N/A

I. Potential application of the research
Vortecone® technology can also apply to pollutant controls in steel manufacturing (Nippon Steel has already shown their strong interests in Vortecone® clean environmental technology).